INVESTIGATION OF COMMUNICATION SYSTEMS FOR LUNAR USE

by

Horace Sammie Allen III, B.S.

A Progress Report

Submitted to

National Aeronautics and Space Administration

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NASA Research Grant NGR-19-003-003

Electrical Engineering Department

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ABSTRACT

This work is concerned with communications on the surface of the Moon and the evaluation of certain communication systems for possible applications on lunar missions.

TABLE OF CONTENTS

ABBREVIATIONS

B	- Receiver bandwidth, Hertz
C	- Capacitance, Farad
COMSAT	- Communications satellite
CSM	- Command service module
CSW	- Continuous seismic waves
dB	- Decibel
dBw	- dB relative to 1 watt
EMU	- Extravehicular mobility unit
EVA	- Extravehicular astronaut
F	- Frequency in megahertz
FM	- Frequency modulation
G	- Conductivity, mhos
Ga	- Antenna gain, dB
Hz	- Hertz
°K	- Degree Kelvin
K	- Boltzmann's constant, Joules/°Kelvin
kHz	- Kilohertz
km	- Kilometer
L	- Inductance, Henry
L_{fs}	- Free space path loss, dB
LM	- Lunar module
mhos	- Conductivity
MHz	- Megahertz

MSFN - Manned space flight network

NASA - National Aeronautics and Space Administration

npd - Noise power density, watts/Hertz

NPD - Noise power density, dBw/Hertz

N_r - Received noise

N_t - Effective noise temperature, watts

N_{th} - Galactic noise received

N_x - Transmitted noise

P_{xt} - Total transmitted power

P_{rt} - Total received power

R - Resistance, Ohms

R_x - Receiver

SNR - Signal to noise ratio

SNR_{in} - System input signal to noise ratio

SNR_{out} - System output signal to noise ratio

SNR_x - $\frac{S_r}{N_r} = \frac{S_x}{N_x}$

S_r - Received signal

S_x - Transmitted signal

T - Effective noise temperature, °Kelvin

T_x - Transmitter

Z_c - Characteristic impedance

ω - Radian frequency

ε_r - Relative dielectric constant

σ - Conductivity

λ_o - Wavelength in meters

β - Phase constant

α_{dB} - Attenuation constant, dB

α - Attenuation constant, nepers

ϕ - Beamwidth of a parabolic antenna

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CONSTANTS AND DEFINITIONS

Distance from Earth to Moon	386,160 km
Boltzmann's constant	$1.38 \times 10^{-23} \frac{\text{Joules}}{°K}$
1 mile	1.609 km
Radius	
a. Earth (Ref. 1)	6,351 km
b. Moon (Ref. 1)	1,738 km
Blackbody temperature	
a. Earth (Ref. 1)	254°K
b. Moon (Ref. 1)	240°K

dB for power is $10\text{Log}_{10}\frac{P_2}{P_1}$

dB for voltage ($R_2 = R_1$) is $20\text{Log}_{10}\frac{V_2}{V_1}$

CHAPTER I

INTRODUCTION

When man's missions on the Moon carry him farther than a few miles from his landing craft he will encounter severe problems with his present communication system. The Moon has two features which will cause severe problems in reliable communications. These are, lack of an atmosphere or ionosphere and an extremely small radius. Due to the lack of an atmosphere or ionosphere long range communication by sky waves will be impossible; therefore, this study will deal only with the surface wave component of the radiated field. The extremely short radius of the Moon will cause the line-of-sight distance to be short as shown in Fig. 1-1, but this distance could be doubled by the use of two antennas the same height above the lunar terrain.

Techniques used for communicating on the Earth will be used on the lunar surface, but a re-evaluation of their effectiveness will be necessary. The astronaut traveling beyond the line-of-sight could communicate with his landing module in several ways. One method of communication would be to use an active repeater, stationed in such a way that both the astronaut and the landing module would be line-of-sight at all times. Lunar Polar Satellites and Earth relay form a system which would be particularly effective, and this system will be evaluated in this report. Another method would be the use of a lunar telephone line to assure communication between astronaut and landing module where lunar terrain might make wireless transmission unfeasible. Calculations to demonstrate the capability of a subsurface link have been included in this report, since it appears that this technique might be useful in the future.

The above mentioned techniques are evaluated on the basis of the weight of equipment required to maintain acceptable standards of reliable communications and system development costs. Due to the large payload delivery cost, techniques requiring the least weight and power are preferred.

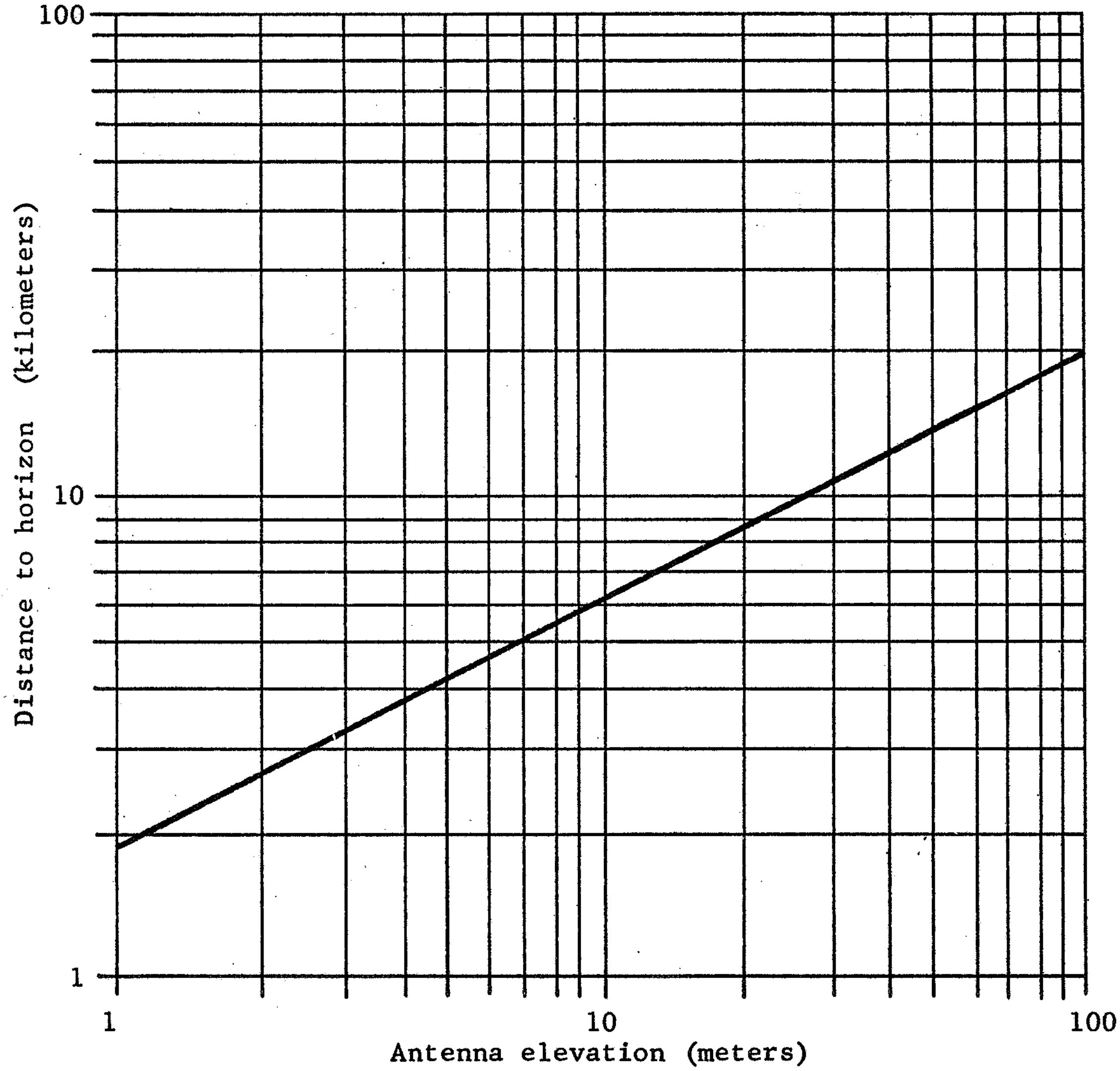


Fig (1-1) Distance to lunar horizon versus antenna height.

CHAPTER II

ARTIFICIAL LUNAR COMMUNICATION SATELLITES

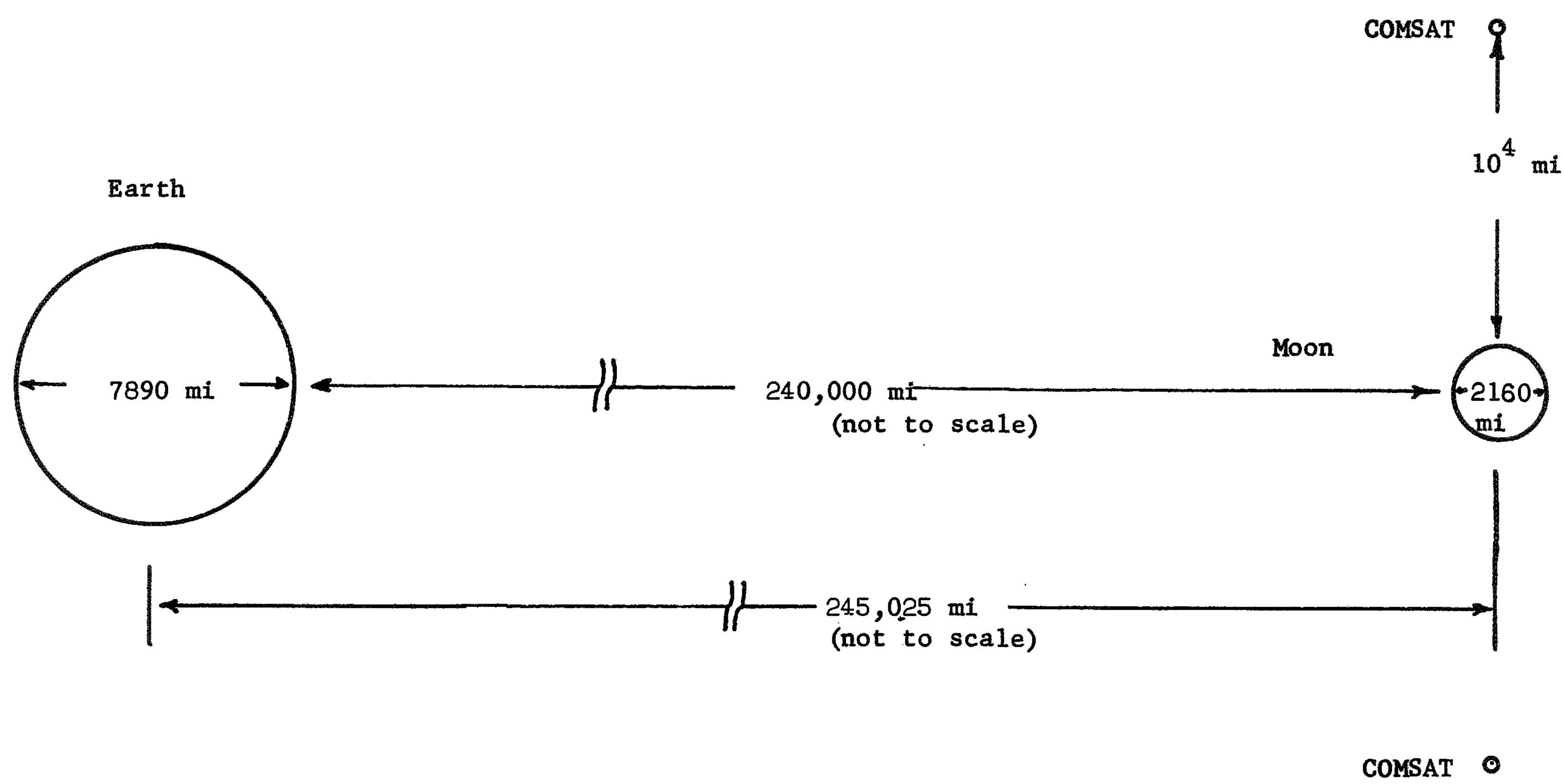
Calculations are presented in this chapter which specify the performance characteristics of a hypothetical lunar satellite system to be used for surface communication on the Moon, and also to be used as a link for the CSM (command service module) during blackout time behind the Moon. The system consists of two satellites in polar orbit (Fig. 2-1) with their plane of rotation always facing the Earth.

The primary links under investigation are LM (lunar module) to COMSAT (communication satellite) and COMSAT (communication satellite) to EMU (extravehicular mobility unit). The operation of this system is limited by a number of factors, such as the transmitter power, range involved, and receiver sensitivity. Based on these constraints, requirements for the proposed relay system can be set forth as follows.

A. Proposed System Requirements

1. Frequency usage

LM to COMSAT link	2.2 GHz
COMSAT to EMU link	2.1 GHz



Fig(2-1) Relay satellite geometry

2. Bandwidth — 3.0 kHz

3. Minimum SNR (signal to noise ratio) at receive input terminals

COMSAT	+14.0 dB
LM	+14.0 dB
EMU	+14.0 dB

4. Maximum power of transmitter

LM	+13.0 dBw
EMU	+13.0 dBw
COMSAT	+20.0 dBw

5. Antennas

LM	10-foot parabolic
EMU	10-foot parabolic
COMSAT	10-foot parabolic

6. Antenna noise temperatures

LM (Ref. 1)	0.0 °K
COMSAT (Ref. 1)	240.0 °K
EMU (Ref. 1)	0.0 °K

B. <u>Justification of the Proposed System Requirements</u>

1. Frequency usage

The selection of the frequency for use in the lunar satellite system is based on two main factors. The first factor is the apparent noise window that exists from approximately 2GHz - 10GHz and the second factor is that the equipment in this frequency range already exists.

2. Bandwidth

The bandwidth was chosen as 3 kHz to accommodate only voice communications using narrow band FM (frequency modulation) techniques, for these sample calculations.

3. Minimum SNR at receiver input terminals

The minimum SNR figures correspond to the requirements of the National Aeronautics and Space Administration (NASA) for ninety percent intelligibility achieved in existing equipment. (Ref. 2)

4. Maximum power of transmitter

The power radiated by the LM or the EMU is determined by existing equipment presently used by astronauts. The 20 dBw transmitter power used for the satellite is a realizable value for a current satellite system.

5. Antennas

These 10-foot parabolic antennas were chosen because of the size considerations in all cases.

6. Antenna noise temperatures

All antenna noise temperatures were selected from Ref. 1 for a 2GHz signal.

C. <u>Design Equations</u>

Listed below are the equations applied to this design. Their derivation is omitted, but a reference is given for each of them in the following bracket.

1. Gain of parabolic antenna (Ref. 3) [2-1]

$$Ga = 20\text{Log}_{10}F + 20\text{Log}_{10}D - 52.6$$

F = frequency, MHz

D = diameter, feet

Ga = antenna gain, dB

2. Beamwidth of parabolic antenna (Ref. 3) [2-2]

$$\phi = \frac{7 \times 10^4}{F \times D} \qquad \phi \leqq 30$$

F = frequency, MHz

D = diameter, feet

ϕ = beamwidth in degrees

3. Free space path loss (Ref. 1) [2-3]

$$L_{fs} = 36.6 + 20\text{Log}_{10}F + 20\text{Log}_{10}D$$

F = frequency, MHz

D = distance, miles

L_{fs} = free space path loss, dB

4. Effective noise temperature (Ref. 1) [2-4]

$$N_t \text{ (watts)} = KTB$$

T = equivalent noise temperature, °Kelvin

K = Boltzmann's constant, Joules/°Kelvin

B = Receiver bandwidth, Hz

N_t = noise power, watts

5. Noise power density (Ref. 3) [2-5]

$npd = KT$

$npd = 1.38 \times 10^{-23} \times T$

$NPD = -228.6 + 10\mathrm{Log}_{10}T$

K = Boltzmann's constant, Joules/°Kelvin

T = °Kelvin

npd = noise power density, watts/Hz

NPD = noise power density, dBw/Hz

6. SNR_{r-act} (derivation in Appendix A) [2-6]

$$SNR_{r-act} = \frac{(SNR_x)\ (SNR_{r-app})}{1 + SNR_x + SNR_{r-act}}$$

See Fig. 2-2

SNR_{r-app} = signal-to-noise ratio at input of EMU receiver considering an infinite signal to noise ratio at COMSAT transmitter.

SNR_x = signal-to-noise ratio actually received by COMSAT.

SNR_{r-act} = actual signal-to-noise ratio received by the EMU which takes into account all noise temperatures encountered by the link.

D. <u>Calculations</u>

Part I - LM to COMSAT

All of the following calculations assume an infinite SNR input to the LM transmitter.

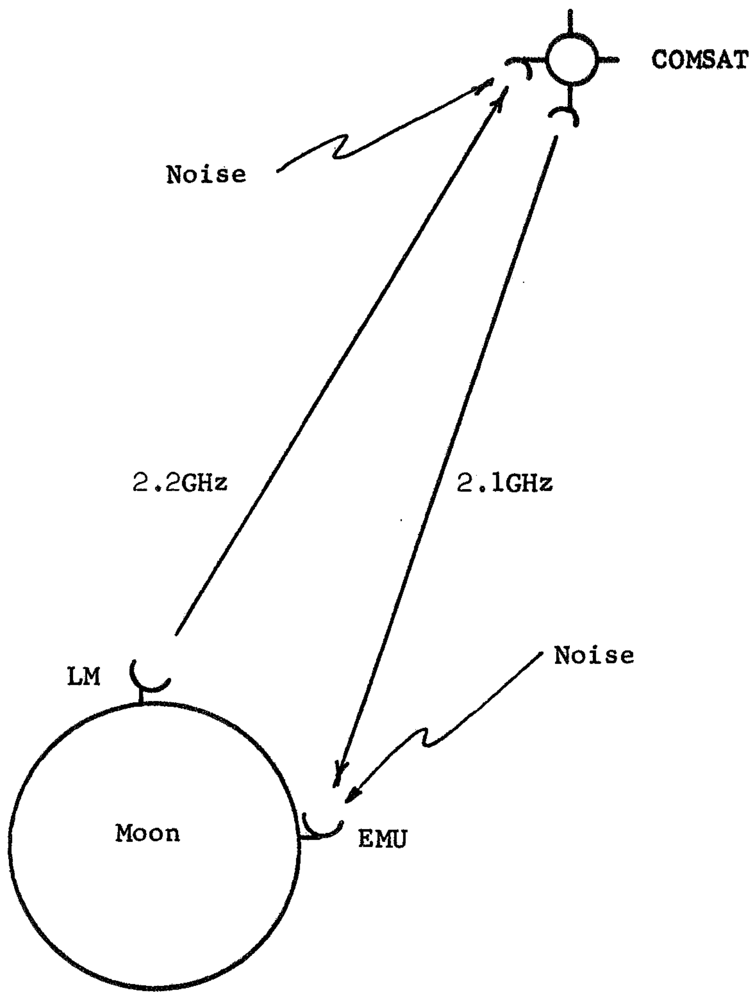
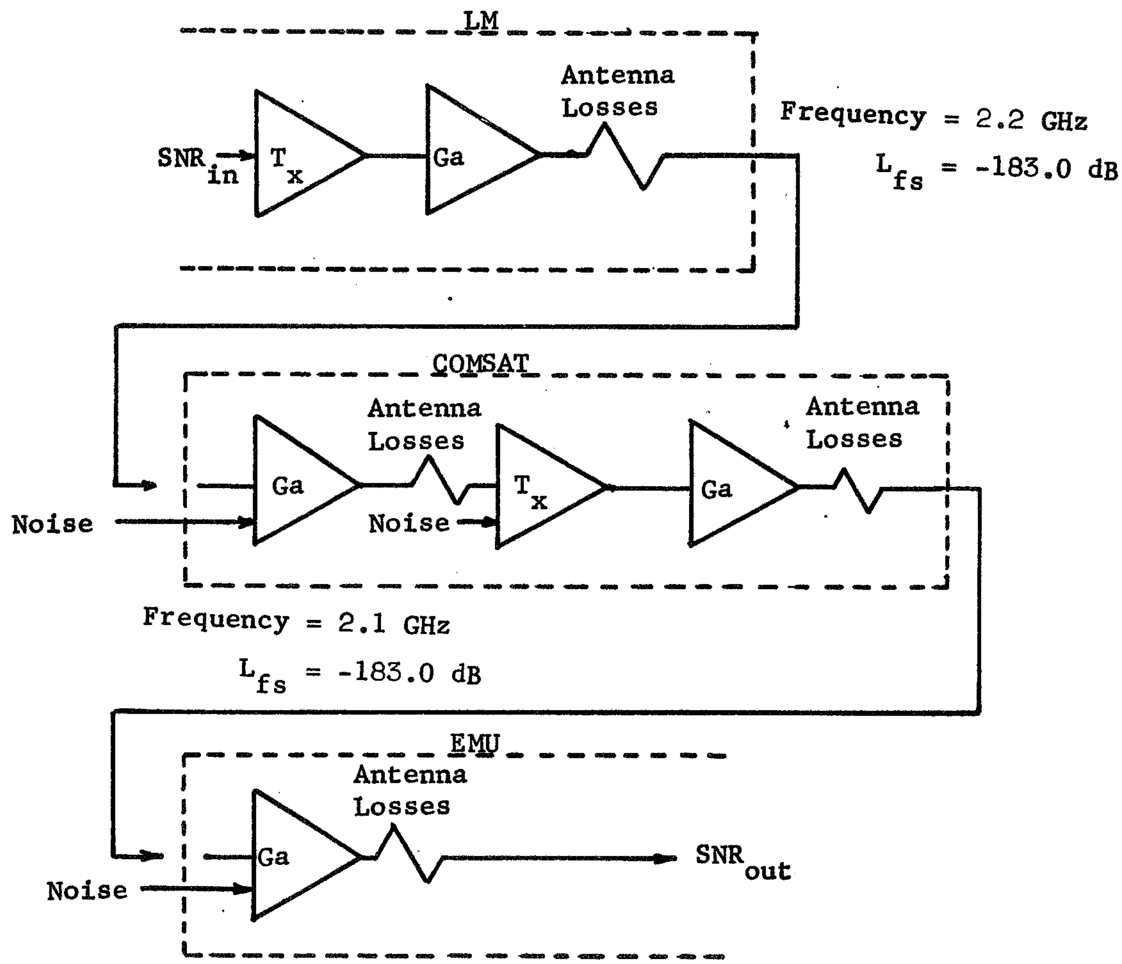


Fig. 2-2 Relay configuration



T_x= Transmitter power

Ga= Antenna gain

SNR_{in}= Signal to noise ratio into transmitter

SNR_{out}= Signal to noise ratio out of the system

Fig.2-3 System under study

LM transmitter power (dBw)	+13.0 dBw
LM bandwidth (kHz)	+3.0 kHz
LM antenna gain (dB)	+34.0 dB
LM antenna circuit loss (dB) (Ref. 2)	-8.9 dB
LM antenna polarization loss (dB) (Ref. 2)	-0.1 dB
LM antenna pointing loss (dB) (Ref. 2)	-2.0 dB
Space loss (L_{fs}), 2.2GHz, 1 X 10^4 miles (dB)	-183.0 dB
ϕ_{LM} (degrees)	+3.18°
COMSAT total received power (dBw)	-147.0 dBw
COMSAT antenna noise temperature (°K) (Ref. 1)	+240.0 °K
ϕ_{COMSAT} (degrees)	+3.18°
COMSAT receiver temperature (°K) (Ref. 4)	+60.0 °K
COMSAT noise temperature total (°K)	+300.00 °K
COMSAT noise density (dBw/Hz)	-204.0 dBw/Hz
COMSAT receiver noise bandwidth (kHz)	+3.0 kHz
COMSAT receiver noise bandwidth (dB)	+35.0 dB
COMSAT total noise power (dBw)	-169.0 dBw
COMSAT carrier predetection SNR_x (dB)	+22.0 dB

Part II - COMSAT to EMU

COMSAT antenna gain (2 X 34dB)	+68.0 dB
COMSAT transmitted power (dBw)	+20.0 dBw
COMSAT antenna circuit loss (2 X 8.9dB) (dB) (Ref. 2)	-17.8 dB
COMSAT pointing loss (2 X 2dB) (dB) (Ref. 2)	-4.0 dB

COMSAT polarization loss (2 X 0.1dB) (dB) (Ref. 2)	-0.2 dB
Space loss (L_{fs}), 2.1GHz, 1 X 10^4 miles (dB)	-183.0 dB
EMU antenna gain (dB)	+34.0 dB
ϕ_{EMU} (degrees)	+3.18°
EMU antenna loss (dB) (Ref. 2)	-8.9 dB
EMU pointing loss (dB) (Ref. 2)	-2.0 dB
EMU polarization loss (dB) (Ref. 2)	-0.1 dB
EMU total receiver signal power (dBw)	-241.0 dBw
EMU total receiver noise power (dBw)	-263.0 dBw
EMU postdetection SNR_{r-act} (dB)	+22.0 dB

The above signal-to-noise calculations show that a lunar satellite system when exposed to the effective noise temperature of the Moon will maintain an acceptable signal-to-noise ratio (Ref. 5) for voice communication. In order to use one or two COMSATs for coverage of the mission, care must be exercised in their placement to insure coverage of the landing area. Lunar satellite system evaluation as compared to the overall systems study appears in the final chapter.

CHAPTER III

EARTH RELAY ANALYSIS

In this chapter use of the Earth as a relay satellite will be evaluated. This system has many advantages, but the most important one is the placement and use of complex equipment in an environment where it can be maintained. Another factor that cannot be overlooked is the fact that the MSFN (Manned Space Flight Network) exists and therefore can be used for this purpose at a savings of many dollars.

The primary links under investigation are LM to MSFN and MSFN to EMU. The operation of a lunar communication system is limited by a number of factors, such as the transmitter power, range, and receiver sensitivity. Based on these constraints, requirements for the proposed relay system can be set forth as follows.

A. Proposed System Requirements

1. Frequency usage

LM to MSFN link	2.2 GHz
MSFN to EMU link	2.1 GHz

2. Bandwidth 3.0 kHz

3. Minimum SNR at receiver input terminals

MSFN	+14.0 dB
LM	+14.0 dB
EMU	+14.0 dB

4. Maximum power of transmitter

MSFN	unlimited
LM	+13.0 dBw
EMU	+13.0 dBw

5. Antennas

LM	10-foot parabolic
EMU	10-foot parabolic
MSFN	60-foot parabolic

6. Antenna noise temperatures

LM (Ref. 1)	254.0 °K
EMU (Ref. 1)	254.0 °K
MSFN (Ref. 1)	240.0 °K

B. Justification of the Proposed System Requirements

1. Frequency usage

The selection of the frequency for use in the Earth relay system is based on two main factors. The first factor is the apparent noise window that exists from approximately 2GHz - 10GHz and the second factor is that communications equipment in this frequency range already exists.

2. Bandwidth

The bandwidth was chosen at 3kHz to accommodate only voice communications using narrow band FM techniques.

3. Minimum SNR at receiver input terminals

The minimum SNR figures correspond to the requirements of the National Aeronautics and Space Administration for ninety percent intelligibility achieved in existing equipment. (Ref. 2)

4. Maximum power of transmitter

Power radiated by the LM or the EMU is determined by existing equipment presently used by astronauts.

5. Antennas

The antennas are selected for their ease of use and situation limitations.

6. Antenna noise temperatures

All antenna noise temperatures were selected from Ref. 3 for a 2 GHz signal.

C. Design Equations

Listed below are the equations applied to this design. Their derivation is omitted, but a reference is given for each of them in the following bracket.

1. Gain of parabolic antenna (Ref. 3) [3-1]

$$Ga = 20\text{Log}_{10}F + 20\text{Log}_{10}D - 52.6$$

F = frequency, MHz

D = diameter, feet

Ga = antenna gain, dB

2. Beamwidth of parabolic antenna (Ref. 3) [3-2]

$$\phi = \frac{7 \times 10^4}{F \times D} \qquad \phi \leqq 30$$

F = frequency, MHz

D = diameter, feet

ϕ = beamwidth in degrees

3. Free space path loss (Ref. 1) [3-3]

$$L_{fs} = 36.6 + 20\text{Log}_{10}F + 20\text{Log}_{10}D$$

F = frequency, MHz

D = distance, miles

L_{fs} = free space path loss, dB

4. Effective noise temperature (Ref. 1) [3-4]

$$N_t \text{ (watts)} = KTB$$

T = equivalent noise temperature, °Kelvin

K = Boltzmann's constant, Joules/°Kelvin

B = receiver bandwidth, Hz

N_t = noise power, watts

5. Noise power density (Ref. 3) [3-5]

$npd = KT$

$npd = 1.38 \text{ X } 10^{-23} \text{ X } T$

$NPD = -228.6 + 10\text{Log}_{10}T$

K = Boltzmann's constant, Joules/°Kelvin

T = °Kelvin

npd = noise power density, watts/Hz

NPD = noise power density, dBw/Hz

6. $SNR_{r\text{-}act}$ (derivation in Appendix A) [3-6]

$$SNR_{r\text{-}act} = \frac{(SNR_x)\ (SNR_{r\text{-}app})}{1 + SNR_x + SNR_{r\text{-}app}}$$

See Fig. 3-1

$SNR_{r\text{-}app}$ = signal-to-noise ratio at input of EMU receiver considering an infinite signal-to-noise ratio at MSFN transmitter.

SNR_x = signal-to-noise ratio actually received by MSFN.

$SNR_{r\text{-}act}$ = actual signal-to-noise ratio received by the EMU which takes into account all noise temperatures encountered by the link.

D. <u>Calculations</u>

Part I - LM to MSFN

All of the following calculations assume an infinite SNR input to the LM transmitter.

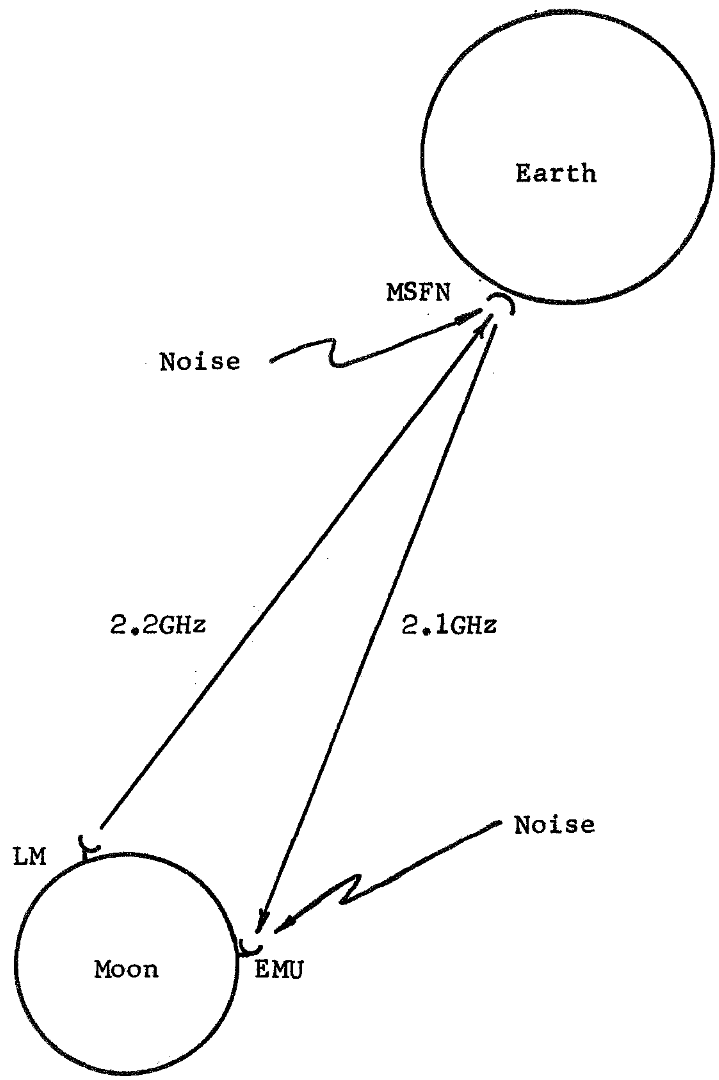


Fig. 3-1 Relay geometry

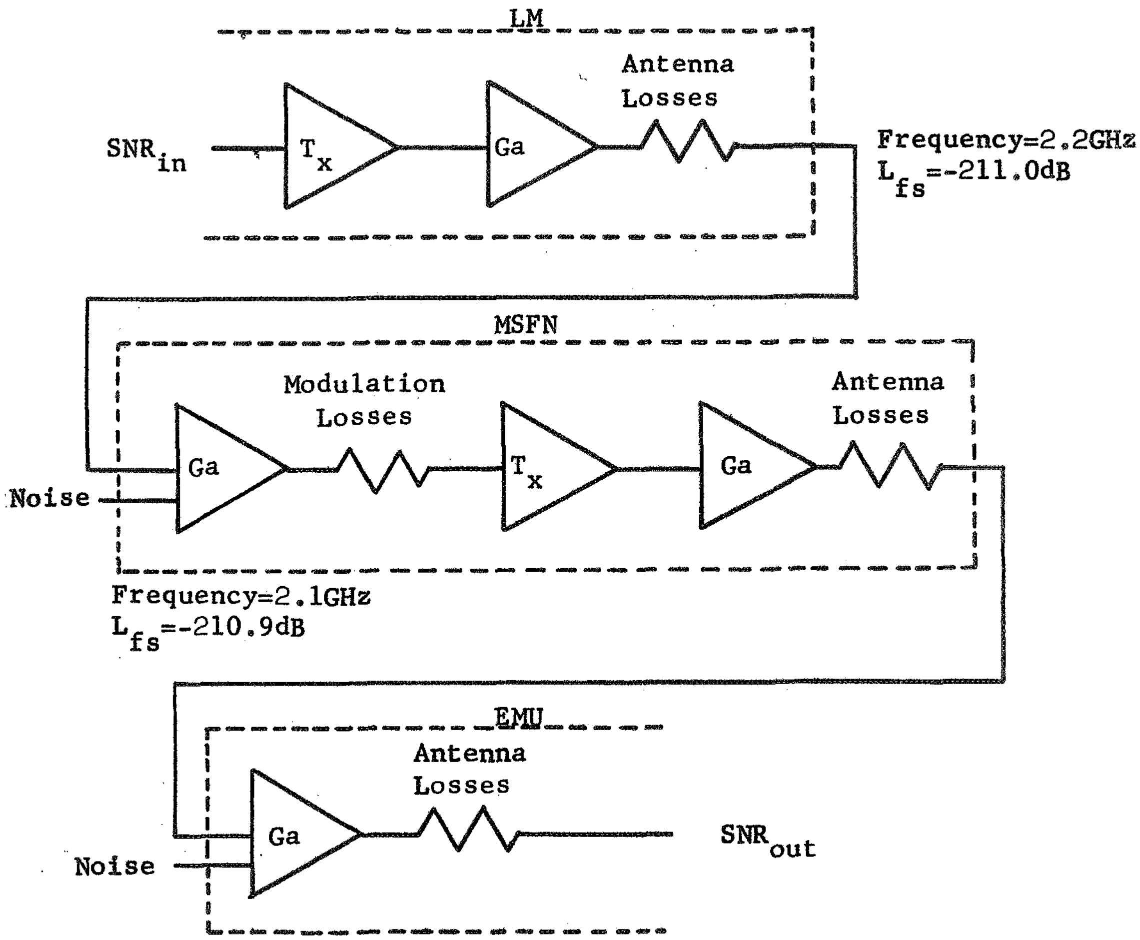


Fig. 3-2 System under study

LM transmitter power (dBw)	+13.0 dBw
LM bandwidth (kHz)	+3.0 kHz
LM antenna gain (dB)	+34.0 dB
LM antenna circuit loss (dB) (Ref. 2)	-8.9 dB
LM antenna polarization loss (dB) (Ref. 2)	-0.1 dB
LM antenna pointing loss (dB) (Ref. 2)	-2.0 dB
Space loss (L_{fs}), 2.2GHz, 2.4 X 10^5 miles (dB)	-211.0 dB
ϕ_{LM} (degrees)	+3.18°
MSFN antenna gain (dB)	+53.0 dB
MSFN total received power (dBw)	-122.0 dBw
MSFN antenna noise temperature (°K) (Ref. 1)	+240.0 °K
MSFN noise density (dBw/Hz)	-204.8 dBw/Hz
MSFN receiver noise bandwidth (dB)	+35.0 dB
MSFN receiver noise power (dBw)	-170.0 dBw
MSFN carrier predetection SNR (dB)	+48.0 dB

Part II - MSFN to EMU

The next calculations for the MSFN to EMU link will assume an infinite SNR_x at the Earth station and an initial receiver carrier power of 0.0 dBw. The SNR_{actual} will be evaluated by equation 3-6.

MSFN transmitted power (dBw)	+40.0 dBw
MSFN carrier modulation loss (dB) (Ref. 2)	-5.5 dB
MSFN antenna gain (dB)	+52.0 dB

ϕ_{MSFN} (degrees)	+0.53°
EMU antenna gain (dB)	+34.0 dB
EMU antenna loss (dB) (Ref. 2)	-8.9 dB
EMU antenna polarization loss (dB) (Ref. 2)	-0.1 dB
EMU antenna pointing loss (dB) (Ref. 2)	-2.0 dB
Space loss (L_{fs}), 2.1GHz, 2.4 X 10^5 miles (dB)	-210.9 dB
EMU received carrier power (dBw)	-101.4 dBw
EMU antenna noise temperature (°K) (Ref. 1)	+254.0 °K
EMU noise density (dBw/Hz)	-204.5 dBw/Hz
EMU receiver noise bandwidth (dB)	+35.0 dB
EMU receiver noise power (dBw)	-169.4 dBw
EMU SNR_{r-app} (dB)	+68.0 dB
EMU SNR_{r-act} (dB)	+27.9 dB

The calculations in this chapter are based on the assumption that the effective noise temperatures encountered by the respective antennas are the total planet blackbody temperatures.

Based on Ref. 5 (ninety percent intelligibility figures) this system will maintain an acceptable SNR. The main drawback for this technique is that only the side of the Moon visible from Earth can be covered. This technique as compared to the other techniques is evaluated in the final chapter.

CHAPTER IV

LUNAR TRANSMISSION LINES

Transmission lines could be used for short range (10 miles - 20 miles) exploratory missions where lunar terrain or the nature of the communication requirement would make wireless transmission unfeasible. These lines could remain as permanent links between field experiments left by astronauts and the lunar landing package.

Two wires separated by the maximum distance compatible with the payout capability of the lunar roving vehicle would be desirable, since this would minimize the attenuation of the transmission line.

A configuration consisting of a pair of insulated wires having a d/r ratio (distance between centers to the wire radius) of ten was chosen after considering the penalty paid in weight of the separation insulation as the d/r ratio is increased and the increased attenuation which results from decreasing d/r.

Aluminum conductors were chosen because of the weight advantage aluminum has over copper, and loading coils were inserted in the aluminum lines to assure an inductance of 200 mh per mile.

A. <u>Proposed System Requirements</u>

1. Frequency usage

LM to EMU link	Base band
EMU to LM link	Base band

2. Bandwidth — 3.0 kHz

3. Minimum SNR at receiver input terminals

LM	+14.0 dB
EMU	+14.0 dB

4. Maximum power of transmitter

LM	Low power
EMU	Low power

B. <u>Justification of the Proposed System Requirements</u>

1. Frequency usage

Base band frequency was chosen for calculations for a lunar telephone system.

2. Bandwidth

The bandwidth was chosen at 3kHz for voice communication calculations.

3. Minimum SNR at receiver input terminals

All figures for SNR are based on ninety percent intelligibility quoted by NASA. (Ref. 2)

4. Maximum power of transmitter

No exact power level was expressed, except that it could be less than one watt.

C. Design Equations

Listed below are the equations for a distortionless line applied to this design. Their derivation is omitted, but a reference is given for each of them in the following bracket.

1. Characteristic impedance (Ref. 6) [4-1]

$$Z_c = [(R + j\omega L)/(G + j\omega C)]^{\frac{1}{2}}$$

R = resistance, Ohms

L = inductance, Henrys

C = capacitance, Farads

G = conductance, mhos

ω = radian frequency, radians/second

Z_c = characteristic impedance, Ohms

2. Attenuation constant (Ref. 6) [4-2]

$$\alpha = [(R) \times (G)]^{\frac{1}{2}}$$

R = resistance, Ohms

G = conduction, mhos

α = attenuation, nepers

3. Attenuation constant (Ref. 7) [4-3]

$$\alpha_{dB} = 8.68 \times [(R) \times (G)]^{\frac{1}{2}}$$

R = resistance, Ohms

G = conduction, mhos

α_{dB} = attenuation, dB

4. Phase constant (Ref. 6) [4-4]

$$\beta = \omega \times [(L) \times (C)]^{\frac{1}{2}}$$

ω = radian frequency

L = inductance, Henrys

C = capacitance, Farads

β = phase, radians

The graph of Fig. 4-2 was constructed from manufacturer's specifications (R, G, L, C) assuming an ideal system without amplitude distortion and transmitting a 1 kHz test signal. The wire is insulated with a 6.0 Mil thickness of material (irradiated polystyrene) having a relative dielectric constant of $\varepsilon_r = 2.4$.

From the graph of Fig. 4-2 it can be seen that reliable communication for short range can be expected with low transmitter power. The usable range of this system is limited only by the sensitivity of the equipment used. Further evaluation of this technique will be included in the last chapter.

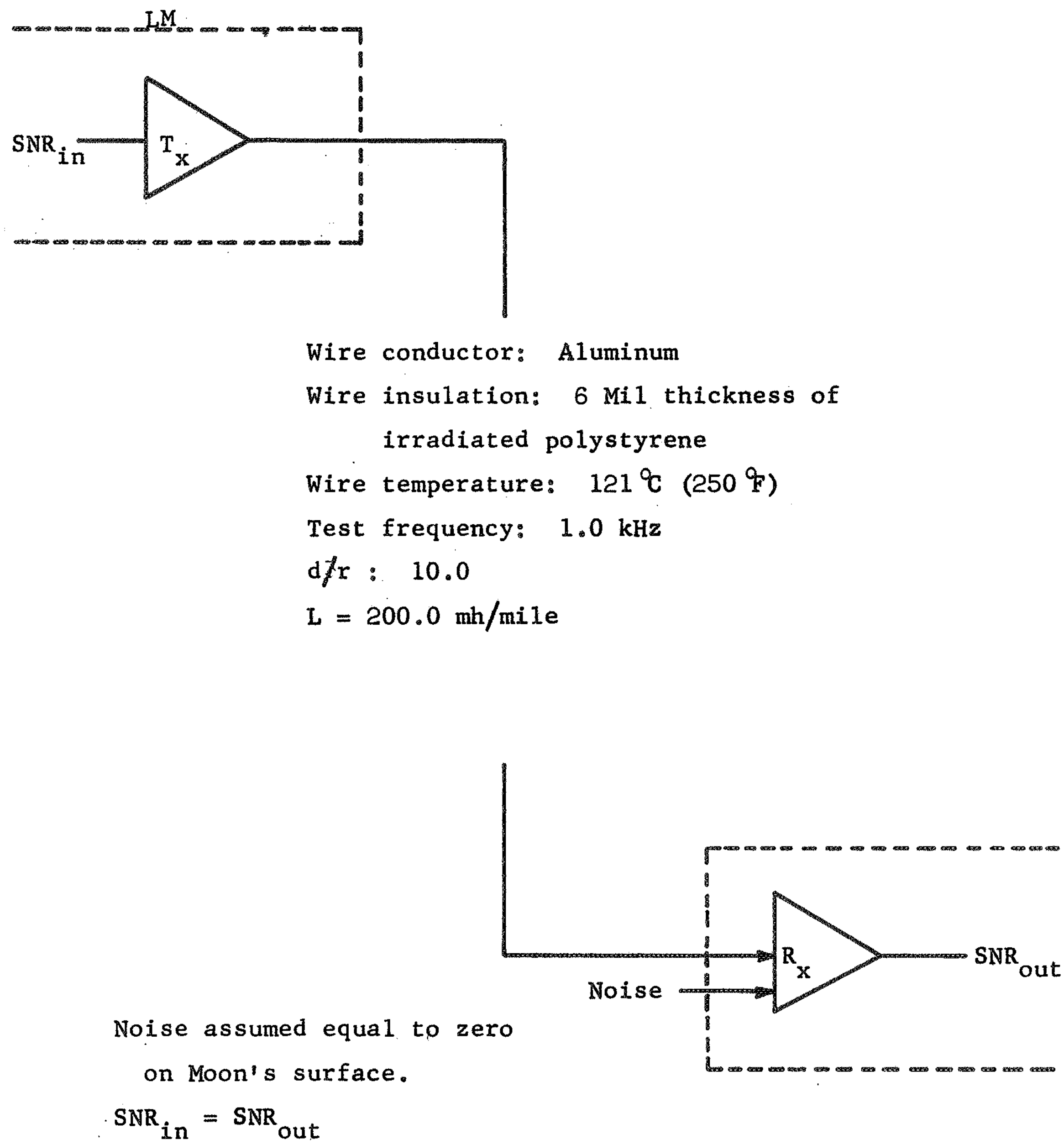


Fig. 4-1 System under study

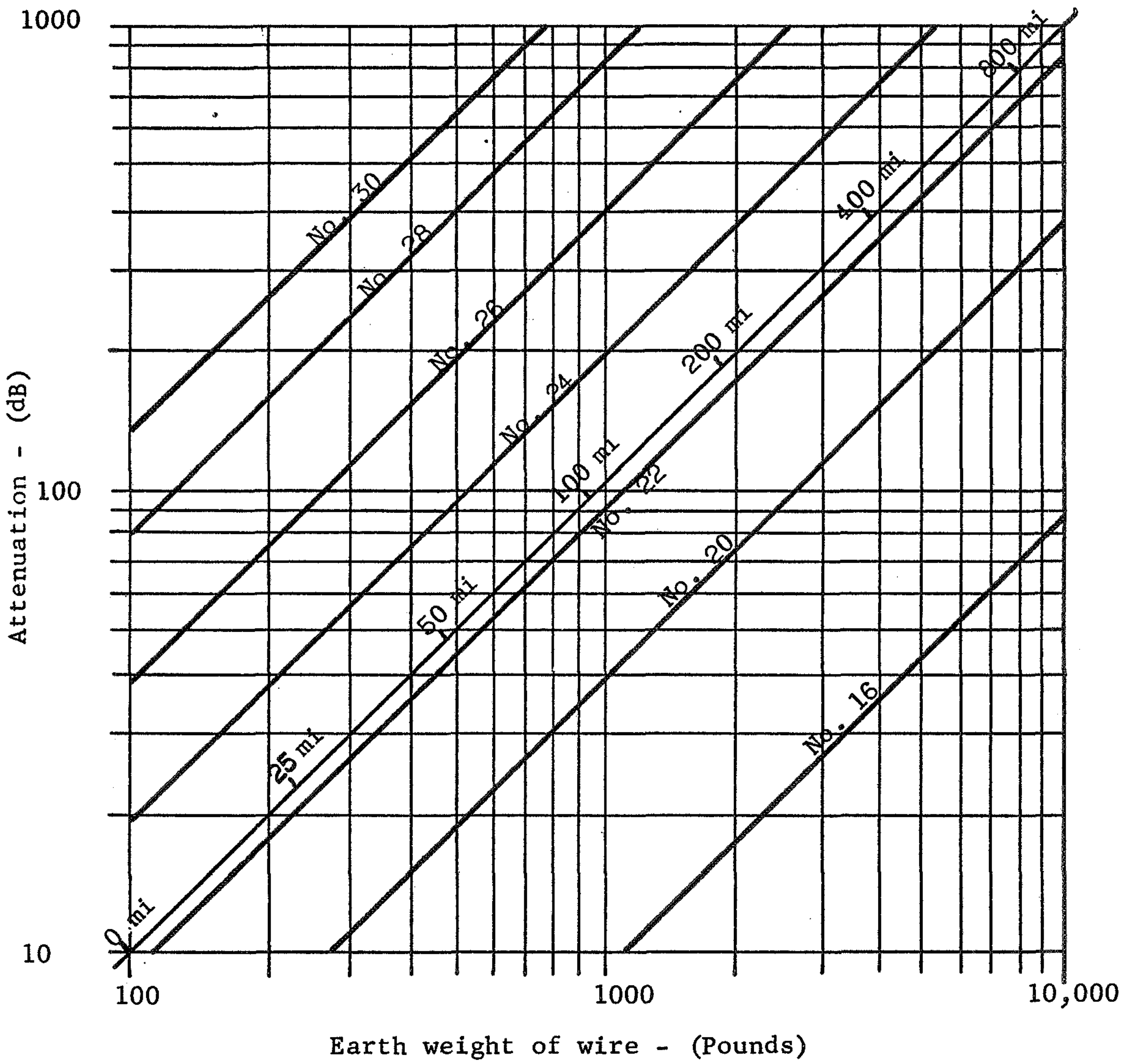


Fig (4-2) - Transmission characteristics of a pair of aluminum wires with loading.

CHAPTER V

SURFACE WAVE COMMUNICATIONS

In this chapter the use of surface waves for beyond line-of-sight transmission will be evaluated. Normally, transmitted energy can reach a source by many paths, utilizing reflection, line-of-sight travel, and bending of the waves around the curvature of the surface, but since the Moon has no atmosphere or ionosphere to reflect waves only energy contained in the surface waves remains to be evaluated for over the horizon communication.

The frequency range of 1.0MHz - 2MHz was chosen for the LM to EMU link because of the increased ground wave losses as the frequency goes above 2MHz and equipment size considerations for operation below 1.0MHz. The frequency for the EVA was chosen at 300MHz because of equipment size considerations and existing NASA apparatus. In the 1MHz - 2MHz band of frequencies the primary noise source was assumed to be galactic noise as shown in Fig. 5-1. For the EVA the primary noise source was considered as a sum of Earth and Moon blackbody temperatures.

The primary links under investigation in this chapter are the LM to EMU link and the EMU to EVA link.

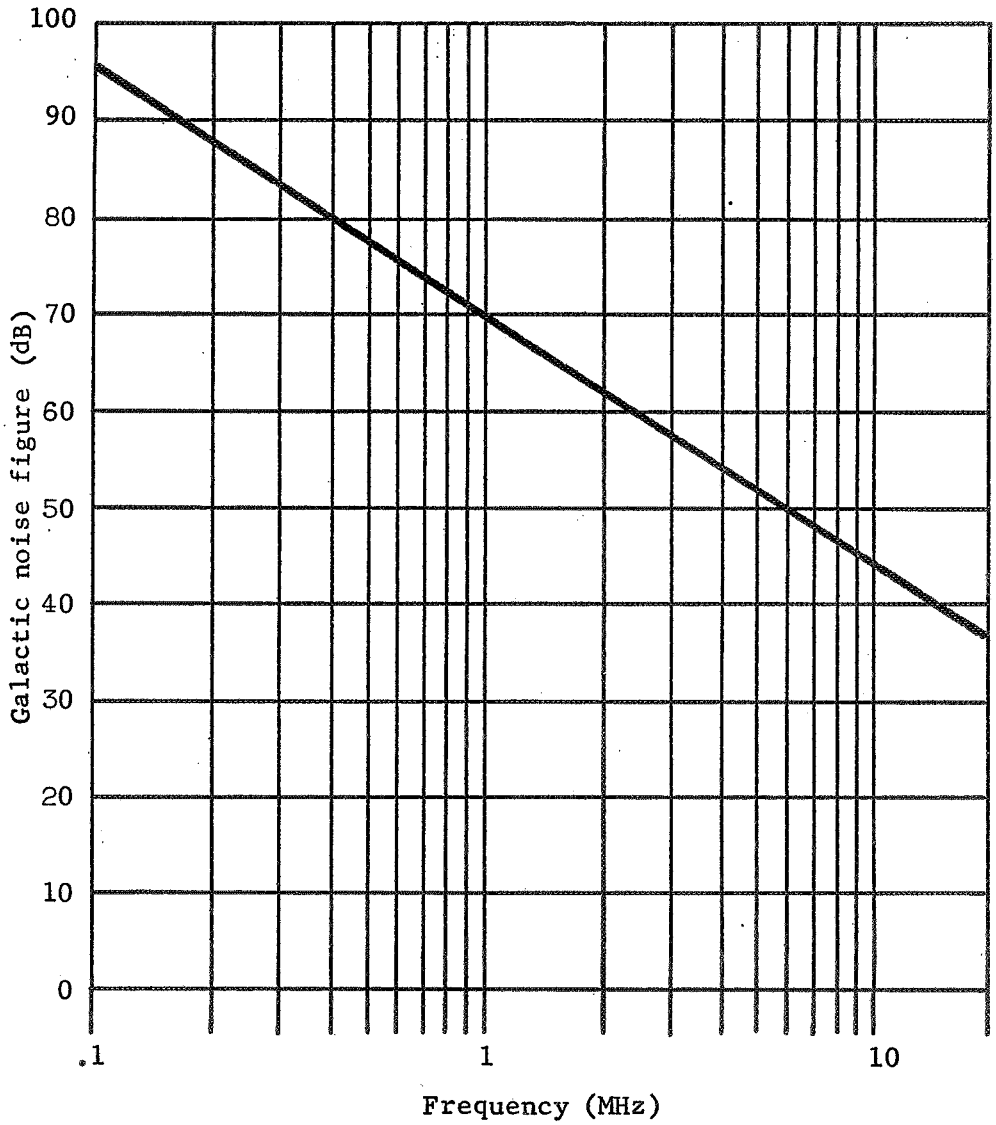


Fig (5-1) Galactic noise versus frequency

A. Proposed System Requirements

1. Frequency usage

LM to EMU link	1.0 MHz - 2 MHz
EMU to LM link	1.0 MHz - 2 MHz
EVA to EMU link	300.0 MHz

2. Bandwidth — 3.0 kHz

3. Minimum SNR at receiver input terminals

LM	+14.0 dB
EMU	+14.0 dB
EVA	+14.0 dB

4. Maximum power of transmitter

LM	+13.0 dBw
EMU	+13.0 dBw
EVA	-3.0 dBw

5. Antennas

LM	100-foot monopole
EMU	100-foot monopole
EVA	8-inch whip

B. Justification of the Proposed System Requirements

1. Frequency usage

The 1MHz - 2MHz frequency band was selected for investigation because low frequency waves have a greater useful communication range, and the equipment size is reasonable. The 300MHz frequency for the EVA was selected because the equipment is small and is already in existence. These frequencies represent extremes and allow one easily to determine the effectiveness of any frequency band between 1MHz and 300MHz by examining the graphs presented in this chapter.

2. Bandwidth

The bandwidth was chosen at 3kHz to accommodate only voice communications using narrow band FM techniques.

3. Minimum SNR at receiver input terminals

Minimum SNR requirements are NASA's existing equipment limitation figures for ninety percent intelligibility. (Ref. 2)

4. Maximum power of transmitter

Power radiated by LM, EMU, or EVA is along lines of existing equipment at NASA.

5. Antennas

LM or EMU antennas were chosen primarily with weight considerations in mind. The antennas used by the EVA are fixed by existing equipment at NASA for 300MHz use.

C. Design Equations

Listed below are the equations for the evaluation of surface wave attenuation. Their derivation is omitted, but a reference is given for each of them in the following bracket.

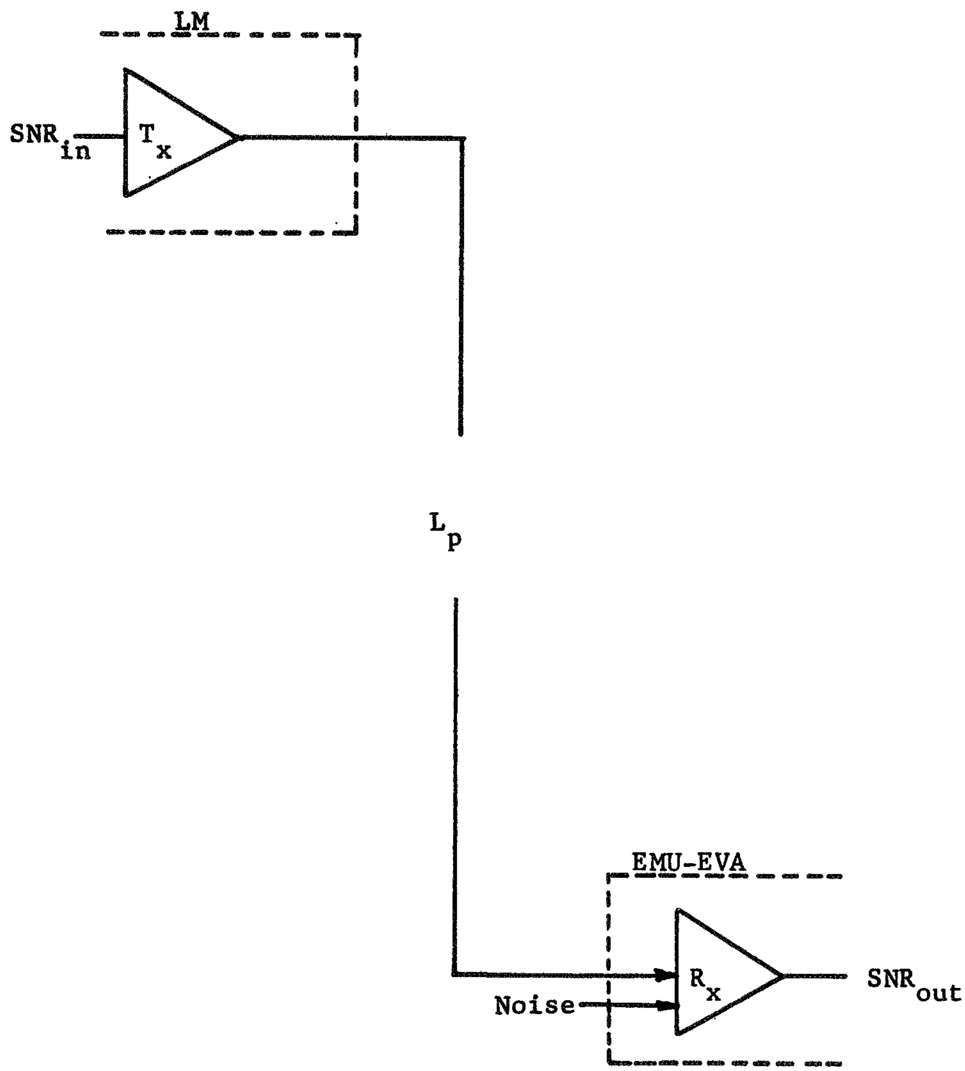


Fig. 5-2 System under study

It is necessary to obtain the reference indicated for graphical evaluation of the surface wave attenuation.

1. Sommerfeld surface wave attenuation function (Ref. 8) [5-1]

$$F_s = \left[1 + j\sqrt{\Pi\omega_s}\, C^{-\omega_s} \operatorname{erfc}\left(-j\sqrt{\omega_s}\right)\right]$$

$$\omega_s = \frac{j\beta R_s \mu^2 (1-\mu^2 \mathrm{Cos}^2\psi)}{2} \left[1 + \frac{\sin\psi}{\mu\sqrt{1-\mu^2\mathrm{Cos}^2\psi}}\right]$$

$$\mu^2 = \frac{1}{\varepsilon_r + jX}$$

$$X = \frac{\sigma}{\omega_s \varepsilon_r} = \frac{(1.79231)(10^{15})\ \sigma_{emu}}{F}$$

$$\operatorname{erfc}\left(-j\sqrt{\omega_s}\right) = \frac{2}{\sqrt{\Pi}} \int_{-j\sqrt{\omega_s}}^{\infty} e^{-v^2}\, dv$$

2. Ground wave attenuation factor (Ref. 8) [5-2]

$\psi = o$

$A = |F_s|$

$A = \left|1 + j\sqrt{\Pi\omega_s}\, e^{-\omega_s} \operatorname{erfc}\left(-j\sqrt{\omega_s}\right)\right|_{\psi=o}$

$A = \left|1 + j\sqrt{\Pi p_1}\, e^{-p_1} \operatorname{erfc}\left(-j\sqrt{p_1}\right)\right|$

$p_1 = pe^{jb}$

p = numerical distance

b = phase constant

$p = \dfrac{\Pi R_s}{\lambda_o X} \mathrm{Cos}\ b$

3. (Ref. 8) [5-3]

$$X = \frac{(1.79231)\ (10^{15})\sigma_{emu}}{F}$$

F = frequency in MHz

σ = conductivity, electromagnetic units

4. (Ref. 8) [5-4]

$$\mathrm{Tan}(b') = \frac{\varepsilon_r - 1}{X}$$

$b' = \mathrm{Tan}^{-1}((\varepsilon_r - 1)/(X))$

ε_r = relative dielectric constant

5. (Ref. 8) [5-5]

$$\mathrm{Tan}(b'') = \frac{\varepsilon_r}{X}$$

$b'' = \mathrm{Tan}^{-1}((\varepsilon_r)/(X))$

ε_r = relative dielectric constant

6. (Ref. 8) [5-6]

$$d_{(p=1)} = \left(\frac{0.0592922}{F}\right) \left(\frac{X \ \mathrm{Cos}\ b'}{\mathrm{Cos}^2\ b''}\right)$$

F = frequency in MHz

$d_{(p=1)}$ = numerical distance at $p=1$

7. (Ref. 8) [5-7]

$b = 2b'' - b'$

8. (Ref. 8) [5-8]

$$K = \left[\frac{\lambda_o}{2\Pi\ ka}\right]^{1/3} \left[\frac{X\ \mathrm{Cos}\ b'}{\mathrm{Cos}^2\ b''}\right]^{1/2}$$

$$K = \left[\frac{0.0309}{F^{1/3}}\right] \left[\frac{X \text{ Cos } b'}{\text{Cos}^2 \text{ b}''}\right]^{1/2}$$

F = frequency in MHz

k = effective radius

a = radius of planet

9. (Ref. 8) [5-9]

$$\eta_o = (k^2 a^2 \lambda_o)^{-1/3}$$

$$\eta_o = (1.0482)(10^{-5})(F)^{1/3}$$

F = frequency in MHz

k = effective radius

a = radius of planet

λ_o = wavelength, meters

10. (Ref. 8) [5-10]

$$E_{(n'=2)} = 2E_o \eta_o \gamma_s$$

$2E_o$ = 0.10 volts/meter

$\eta_o = (a^2 \lambda_o)^{-1/3}$

a = radius of lunar surface, meters

λ_o = wavelength, meters

γ_s = evaluated from graphs (Ref. 8)

$E_{(n'=2)}$ = voltage per meter at distance n'=2

11. (Ref. 8) [5-11]

$$d_{n'=2} = 2/\beta_o \eta_o$$

β_o = evaluated from graphs (Ref. 8)

$\eta_o = (a^2 \lambda_o)^{-1/3}$

a = radius of lunar surface, meters

λ_o = wavelength, meters

12. Effective noise temperature (Ref. 1) [5-12]

$N_t(\text{watts}) = KTB$

T = equivalent noise temperature, °Kelvin

K = Boltzmann's constant, Joules/°Kelvin

B = receiver bandwidth, Hz

N_t = noise power, watts

13. Noise power density (Ref. 3) [5-13]

npd = KT

npd = $1.38 \times 10^{-23} \times T$

NPD = $-228.6 + 10\text{Log}_{10}T$

K = Boltzmann's constant, Joules/°Kelvin

T = °Kelvin

npd = noise power density, watts/Hz

NPD = noise power density, dBw/Hz

Fig. 5-3 was constructed to show surface wave attenuation as a function of distance along the lunar terrain. The lunar model assumed is that of a smooth, homogeneous speroid of radius r_o = 1738 km. The effects of rough terrain have been neglected in this study, although it is recognized that rough terrain will have a definite effect upon the attenuation function.

The following is a statement of curve parameters for Fig. 5-3.

Curve 1.

Frequency = 1.0 MHz

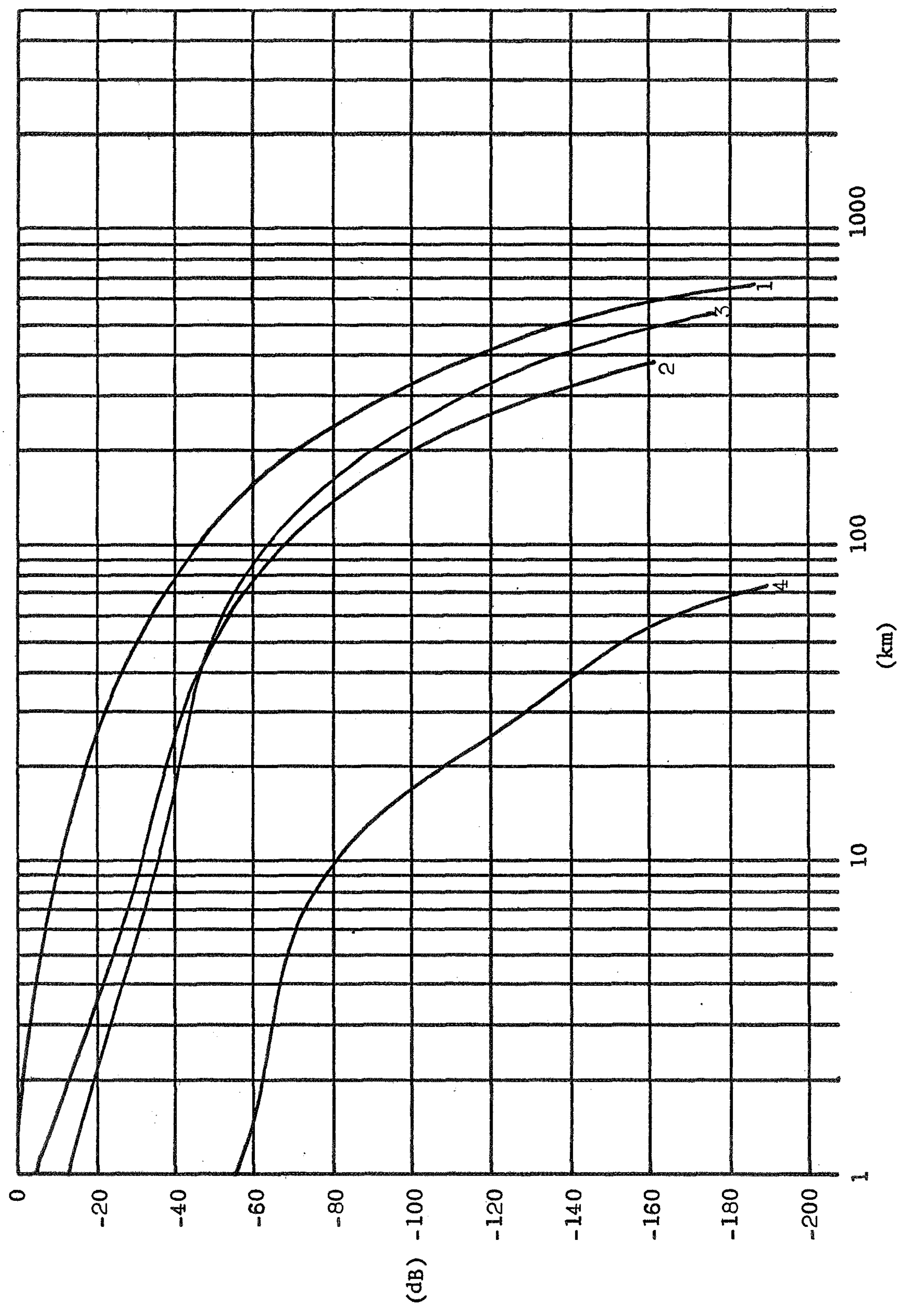


Fig (5-3) Lunar Attenuation versus Distance (kilometers)

$\sigma = 1 \times 10^{-3}$ mhos/m

$\varepsilon_r = 2.4$

Curve 2.

Frequency = 2.0 MHz

$\sigma = 1 \times 10^{-3}$mhos/m

$\varepsilon_r = 2.4$

Curve 3.

Frequency = 1 MHz

$\sigma = 1 \times 10^{-4}$ mhos/m

$\varepsilon_r = 2.4$

Curve 4.

Frequency = 300.0 MHz

$\sigma = 1 \times 10^{-3}$ mhos/m

$\varepsilon_r = 2.4$

D. Calculations

Part I - LM to EMU

All of the following calculations assume an antenna noise temperature of 1×10^{7} °K, and infinite SNR at LM.

LM transmitter frequency (MHz)	+1.0 MHz
Terrain conductivity (mhos/m)	$+1.0 \times 10^{-3}$ mhos/m
LM transmitter power (dBw)	+20.0 dBw
LM bandwidth (kHz)	+3.0 kHz
LM antenna gain (dB)	+0.0 dB
Path loss (LP), $\sigma=10^{-3}$, 450km (dB)	-120.0 dB

EMU antenna gain	+0.0 dB
EMU total received power (dBw)	-100.0 dBw
EMU antenna noise temperature (°K) (Ref. 1)	+1.0 x 10^7 °K
EMU NPD (dBw/Hz)	-158.6 dBw/Hz
EMU bandwidth (dB)	+35.0 dB
EMU receiver noise power (dBw)	-123.6 dBw
EMU carrier predetection SNR (dB)	+23.6 dB

Part II - LM to EMU

All of the following calculations assume an antenna noise temperature of 1 X 10^8 °K, and infinite SNR at LM.

LM transmitter frequency (MHz)	+1.0 MHz
Terrain conductivity (mhos/m)	+1.0 X 10^{-3} mhos/m
LM transmitter power (dB)	+20.0 dB
LM bandwidth (kHz)	+3.0 kHz
LM antenna gain (dB)	+0.0 dB
Path loss (Lp), $\sigma = 10^{-3}$, 450km (dB)	-120.0 dB
EMU antenna gain (dB)	+0.0 dB
EMU total received power (dBw)	-100.0 dBw
EMU antenna noise temperature (°K) (Ref. 1)	+1.0 X 10^8 °K
EMU NPD (dBw/Hz)	-148.6 dBw/Hz
EMU bandwidth (dB)	+35.0 dB
EMU receiver noise power (dBw)	-113.6 dBw
EMU carrier predetection SNR (dB)	+13.0 dB

Part III - EVA to EMU

All of the following calculations assume an infinite SNR at EVA.

EVA transmitter frequency (MHz)	+300.0 MHz
Terrain conductivity (mhos/m)	+1.0 X 10^{-3} mhos/m
EVA transmitter power (dB)	-3.0 dB
EVA bandwidth (kHz)	+3.0 kHz
EVA antenna gain (dB)	+0.0 dB
Path loss (Lp), $\sigma = 10^{-3}$, 54km (dB) (Fig. 5-3)	-150.0 dB
EMU antenna gain (dB)	+0.0 dB
EMU total received power (dBw)	-153.0 dBw
EMU antenna noise temperature (°K) (Ref. 1)	+494.0 °K
EMU NPD (dBw/Hz)	-201.7 dBw/Hz
EMU bandwidth (dB)	+35.0 dB
EMU receiver noise power (dBw)	-166.7 dBw
EMU carrier predetection SNR (dB)	+13.7 dB

From the calculations presented in this chapter it is seen that reliable communication by surface wave can be expected from the proposed system as long as stated ranges are not exceeded. Further evaluation of this technique is included in the last chapter.

CHAPTER VI

COMMUNICATION BY SUBSURFACE WAVES

In this chapter the use of subsurface waves for communications will be evaluated. The propagation medium is considered to be infinite in extent, homogeneous and isotropic, and characterized by the electrical constants μ, ε, and σ, which are assumed independent of frequency. This study shows that only narrow band modulation techniques such as on-off keying, PM or FSK at low bit rates are feasible.

The use of subsurface antennas is the proposed method of wave generation. The author realizes that the results shown in this chapter will not be exact due to the variation of propagation medium electrical constants, and slips that exist in lunar surface bed rock.

Tabulated results in this chapter will be made assuming a receiver sensitivity figure of 1.0×10^{-6} volts for 20.0 dB SNR out of the receiver. This method of communication is included for completeness despite its apparent limitations in practical applications.

A. Proposed System Requirements

1. Frequency usage

EMU to LM	0.5 kHz - 10.0 kHz
LM to EMU	0.5 kHz - 10.0 kHz

2. Bandwidth — Narrow

3. Maximum power of transmitter

EMU	+13.0 dBw
LM	+13.0 dBw

B. Justification of the Proposed System Requirements

1. Frequency usage

The frequency range of 0.5kHz - 10.0kHz was chosen to give typical path loss figures for several frequencies.

2. Bandwidth

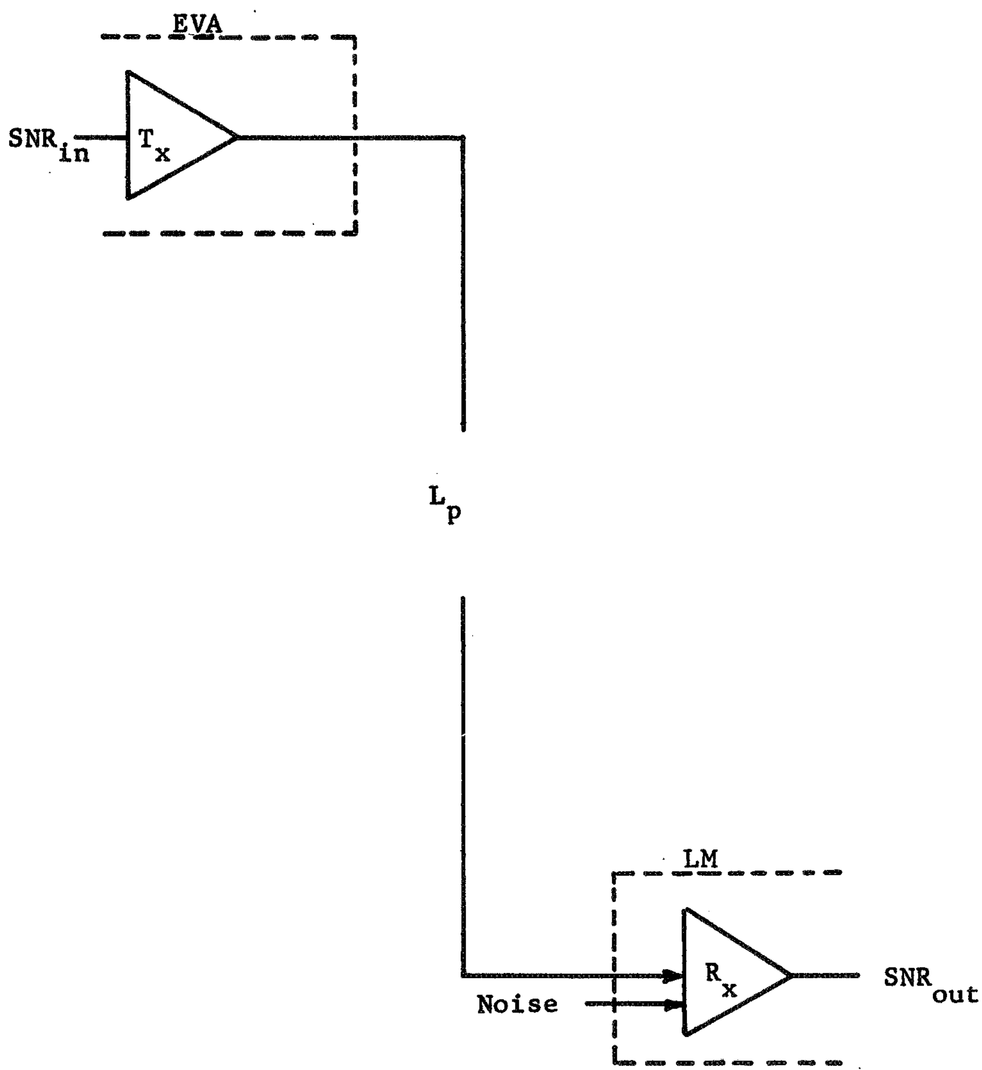
Very narrow because of the necessary low operating frequency.

3. Maximum power of transmitter

The maximum power of the transmitter was set with h weight limitations in mind.

C. Design Equations

Listed below are the equations for the evaluation of subsurface wave attenuation. Their derivation is omitted, but a reference is given for each of them in the following bracket and additional information is contained in Appendix B.



Noise assumed equal to zero

Fig.6-1 System under study

1. Loss tangent P (Ref. 9) [6-1]

The loss tangent P is a dimensionless ratio of the conduction to the displacement currents.

$$P = \frac{\sigma/\omega}{\varepsilon} = \frac{60\lambda_o}{\varepsilon_r} = \frac{(18)(10^3)(\sigma)}{(F)(\varepsilon_r)}$$

σ = conductivity, mhos/m

F = frequency, MHz

ε_r = relative dielectric constant

λ_o = wavelength in meters

ω = radian frequency, radian/second

2. L_p (path loss) (Ref. 9) [6-2]

$L_p = L_s A_x$

L_s = spreading loss = $(4\Pi R_d/\lambda)^2$

A_x = exponential damping loss = $e^{2\alpha_x R_d}$

$\alpha_x = (F\sigma)^{1/2}/(15.92)$, nepers/meter

R_d = distance between communicators, meters

$\lambda = (100)/(F\sigma)^{1/2}$, meters

L_p = path loss, nepers/meter

3. L_p (dB) (path loss) (Ref. 9) [6-3]

$L_p = L_s(\text{dB}) + A_x(\text{dB})$

$L_p = -18.02 + 20\text{Log}_{10}R_d$ (meters) $+ 10\text{Log}_{10}(F_k\sigma)$

$+878.3(F_k\sigma)^{1/2}R_d$ (miles)

F_k = frequency, kHz

σ = conductivity, mhos/meter

L_p = path loss, dB

D. Calculations

Part I - EVA to LM

All of the following calculations assume no noise below the surface of the Moon.

EVA transmitted power (dBw)	+0.0 dBw
Terrain conductivity (mhos/m)	1×10^{-4} mhos/m
Transmitted frequency (Hz)	500.0 Hz
Path loss (L_p), at F = 500.0 Hz, 13 miles (dB)	-120.0 dB
LM received power (dB)	-120.0 dB
LM received volts (v)	$+1 \times 10^{-6}$ volts
LM SNR out of receiver (dB)	+20.0 dB

The operating range of this system, with zero noise, is limited only by the capability of the equipment used. In a practical application, with noise present, the use of filters would extend the operating range considerably. Fig. 6-2 shows the path attenuation expected from a homogeneous Earth.

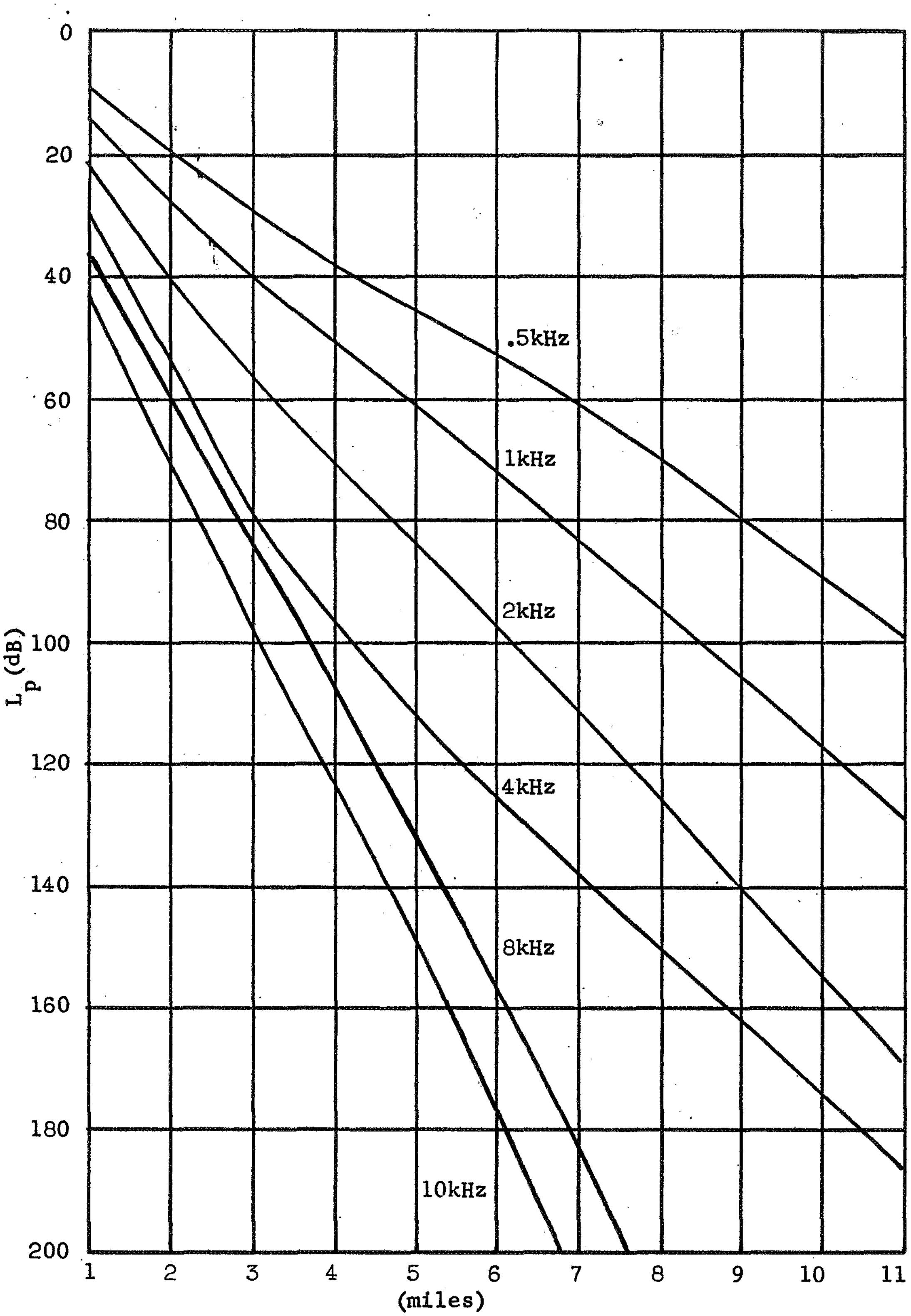


Fig. 6-2 Propagation loss (L_p) vs range, $\sigma=10^{-4}$ mhos per meter.

CHAPTER VII

RESULTS AND CONCLUSIONS

Five communication techniques applicable to lunar conditions have been evaluated. The major characteristics of these techniques are summarized in Table I. Table II lists the relative advantages and disadvantages of each technique.

The author has made no attempt to select the best possible technique because there is no one clear-cut best solution. The solution will depend upon the requirements of each individual mission.

For example, missions requiring only voice communications between a lunar landing module and a lunar roving vehicle, with a maximum distance of 30 miles from base, a surface wave system might be selected.

For missions greater than 280 miles on the visible side of the Moon, lunar satellites or Earth relay could be used. The use of lunar satellites would also add the capability of continuous communication with the CSM. For each mission there might be several techniques applicable or combinations of techniques. In each case the mission will determine which of the five techniques could be used best.

TABLE I

PERFORMANCE CHARACTERISTICS

	BANDWIDTH	RANGE	POWER REQUIREMENTS
COMSAT	Wideband	Not limited if coverage is planned, additional coverage of CSM during blackout time.	+20dBw
Earth Relay	Wideband	Limited only to visible side of Moon.	+20 dBw
Lunar Transmission lines	Narrow	Only limited by weight of wire carried.	1 watt or less
Surface Waves	Narrow	Limited by electrical constants of the surface over which the propagation occurs.	+20dBw
Subsurface Waves	Extremely Narrow	Limited by terrain electrical constants along with geological obstructions.	+13 dBw

TABLE II

ADVANTAGES AND DISADVANTAGES

	ADVANTAGES	DISADVANTAGES
COMSAT	Provides complete continuous coverage of landing party, communications with CSM at all times, and a wide bandwidth.	The high cost of development, requires active device in lunar orbit, lunar surface antennas must have satellite tracking and acquisition capability, and many are required for complete coverage.
Earth Relay	Antenna tracking capability is not required, existing equipment can be used, complete coverage of the visible side of the Moon is possible and wideband communications.	Significant delay time, no coverage of non-visible side of the Moon, and ties up MSFN equipment, limits usefulness.
Lunar Transmission Lines	Not limited at all by line-of-sight, and can be left for permanent experiment links.	The large weight of wire required for medium distances may be prohibitive.
Surface Waves	The development costs are small.	Narrow bandwidth, large inefficient antennas, and high power for long (greater than 500 miles) range applications limit capabilities.
Subsurface Waves	Reliable communications regardless of lunar surface conditions.	Installation problems, high power, and limited to short range.

APPENDIX A

EFFECTS OF TRANSMITTED NOISE ON RECEIVER SNR's

The purpose of this appendix is to present a method for calculating receiver signal-to-noise ratios (SNR's) for channels over which noise, in addition to signal, is transmitted. In most well-designed systems, the transmitted noise is insignificant (transmit SNR > 30 dB) and only thermal noise is considered at the receiver. This, however, is not always the case, as is shown by considering the relay communication system discussed in this report. Since the signal-to-noise ratio received at the relay point is low (<20 dB) a significant amount of noise is transmitted from the relay to the end point. The type of transmission considered here is that of a peak-power-limited channel in which signal power is decreased as noise power is added, resulting in a constant total transmitted power.

Total transmitted and received powers may be expressed as

$$P_{xt} = S_x + N_x = \text{constant} \qquad \text{[A-1]}$$

$$P_{rt} = S_r + N_r \qquad \text{[A-2]}$$

Defining SNR_{r-app} as the apparent signal-to-noise ratio at the receiver calculated using P_{rt} (assuming an infinite transmitted SNR),

$$SNR_{r\text{-}app} = \frac{P_{rt}}{N_{th}} \qquad [A\text{-}3]$$

$$= \frac{S_r + N_r}{N_{th}}, \text{ when noise is transmitted.} \qquad [A\text{-}4]$$

The actual signal-to-noise ratio at the receiver may be expressed as

$$SNR_{r\text{-}act} = \frac{S_r}{N_r + N_{th}} \qquad [A\text{-}5]$$

$$= \frac{1}{\dfrac{N_r}{S_r} + \dfrac{N_{th}}{S_r}} \qquad [A\text{-}6]$$

$$= \frac{1}{\dfrac{N_r}{S_r} + \dfrac{(N_{th})\left[1 + \dfrac{N_r}{S_r}\right]}{(S_r)\left[1 + \dfrac{N_r}{S_r}\right]}} \qquad [A\text{-}7]$$

$$= \frac{1}{\dfrac{N_r}{S_r} + \dfrac{N_{th}}{S_r + N_r}\left\{1 + \dfrac{1}{SNR_x}\right\}} \qquad [A\text{-}8]$$

but

$$\frac{N_{th}}{S_r + N_r} = \frac{N_{th}}{P_{rt}} = \frac{1}{SNR_{r\text{-}app}} \qquad [A\text{-}9]$$

and

$$\frac{N_r}{S_r} = \frac{1}{SNR_x} = \frac{N_x}{S_x} \qquad [A\text{-}10]$$

therefore,

$$SNR_{r\text{-}act} = \frac{1}{\dfrac{1}{SNR_x} + \dfrac{1}{SNR_{r\text{-}app}}\;\dfrac{SNR_x + 1}{SNR_x}} \qquad [A\text{-}11]$$

$$= \frac{1}{\dfrac{SNR_{r-app} + SNR_x + 1}{(SNR_x)\quad(SNR_{r-app})}} \qquad [A-12]$$

$$SNR_{r-act} = \frac{(SNR_x)\quad(SNR_{r-app})}{1 + SNR_x + SNR_{r-app}} \qquad [A-13]$$

APPENDIX B

In general, and assuming that all time variations are as $e^{j\omega t}$, Maxwell's equations and the wave equations are

$$\nabla \times \overline{H} = \varepsilon_o \frac{\partial \overline{E}}{\partial t}$$

$$\nabla \times \overline{E} = \mu_o \frac{\partial \overline{H}}{\partial t}$$

$$\nabla \cdot \overline{E} = o$$

$$\nabla \cdot \overline{H} = o$$

$$\nabla^2 \overline{E} = -\omega^2 \mu\varepsilon \overline{E} \qquad [B-1]$$

$$\nabla^2 \overline{H} = -\omega^2 \mu\varepsilon \overline{H}$$

From equation B-1, assuming E_x to vary only with z, we find

$$\frac{d^2 E_x}{d z^2} = -\omega^2 \mu\varepsilon E_x \qquad [B-2]$$

with $E_x = f(z,t)$.

A solution in the form

$$E_p e^{-\gamma z} e^{-j\omega t}$$

E_p = peak value

with

$$\gamma^2 = -\omega^2 \mu\varepsilon \quad \text{is used.} \qquad [B-3]$$

The effect of including the conductivity σ is that the factor $j\omega\varepsilon$ has now become $\sigma + j\omega\varepsilon$. We may therefore calculate the new propagation constant.

$$\gamma^2 = (\sigma + j\omega\mu) j\omega\mu$$

$$\gamma = j\omega\sqrt{\mu\varepsilon}\sqrt{1 - j\frac{\sigma}{\omega\varepsilon}} \qquad \text{[B-4]}$$

The positive sign was retained to allow positive numerical values for α and β, and hence corresponds to propagation in the +z direction. We further define

$$p \equiv \frac{\sigma}{\omega\varepsilon}$$

$$k \equiv j\gamma$$

and continue with [B-4] to get

$$\beta - j\alpha = -\omega \sqrt{\mu\varepsilon}\,\sqrt{1 - jp}\ , \qquad \text{[B-5]}$$

$$\sqrt{1 - jp} \equiv f(p) - jG(p)$$

and

$$\alpha = \omega\sqrt{\mu\varepsilon}\ G(p) \text{ nepers/meter} \qquad \text{[B-6]}$$

G(p) and F(p) are given by

$$G(p) = \left[1/2 \left((1+p)^{1/2}) - 1\right)\right]^{1/2} \qquad \text{[B-7]}$$

$$F(p) = \left[1/2 \left((1+p)^{1/2} + 1\right)\right]^{1/2} \qquad \text{[B-8]}$$

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